ON PV MODULE TEMPERATURES IN TROPICAL REGIONS – A COMPARISON BETWEEN SYSTEM LOCATIONS IN SINGAPORE AND BRAZIL

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Abstract. *Several influencing factors which include rooftop material, ventilation, module framing and other environmental aspects were analysed for selected photovoltaic (PV) systems in Singapore (~1°20'N, 103°40'E). The variance of the module temperatures was far greater than that of the ambient temperatures in the sites under investigation. An additional tropical region was selected, with 3 PV systems in Brazil (two in Florianópolis and one in Belo Horizonte). The curve fitting profiles were in line with the methodology derived in Singapore. Areas of improvement in order to reduce module temperatures are suggested, which eventually would lead to an optimized system performance in tropical regions.*

Keywords: *photovoltaic systems, module temperature, tropical regions.*

1. INTRODUCTION

The efficiency of photovoltaic (PV) systems is heavily affected by their operating module temperature. For silicon wafer-based technology, every 1°C of module temperature above the 25°C used in the so-called Standard Test Conditions (STC), causes an approximate 0.45% loss in module efficiency (Mau and Jahn, 2006; Skoplaki and Palyvos, 2009). For thin-film systems, such a drop would be only about half or less (Rüther *et al.*, 2004). Also, among all involved losses of performance in PV systems in the tropics, the operating temperature can be accounted for almost 50% (Nobre *et al.*, 2012). Among the many models correlating module temperature and weather variables such as ambient temperature, irradiance and wind speed, the simplest and most widely implemented one is given by the formula

$$T_{mod} = T_{amb} + k \cdot G_{mod} \tag{1}$$

where T_{mod} and T_{amb} are the module and ambient temperature respectively, G_{mod} is the irradiance on the plane-of-array of the PV system and k is the slope called Ross coefficient, expressing the rise in module above ambient temperature with increasing irradiance (Ross, 1976). Most past research has reported the range of k to be 0.02-0.04°C·m^2/W (Buresch, 1983), with the value of k = 0.025°C·m^2/W being the most broadly accepted (Sauer and Kaiser, 1994). Other models which consider the influence of the wind have been derived (King *et al.*, 2004; Skoplaki and Palyvos, 2009) with more comprehensive investigations taken place recently (Koehl *et al.*, 2011; Kurnik *et al.*, 2011).

With the growth of worldwide PV markets continuing to be astonishing, rising from 16.6 GWp new installed capacity in 2010 to 27.7 GWp in 2011 (+67%) (EPIA, 2011), it is important to note that most of this installed capacity of systems continues to take place primarily in Europe (~75% of the market), Japan, United States, South Korea and China. Consequently, only a small fraction of PV installations in the world are located in tropical regions. With more large photovoltaic (PV) markets emerging in tropical areas (such as Thailand, Malaysia, parts of India and Brazil) under challenging climate conditions (constantly high temperatures and high humidity), PV systems will have to be specifically designed for the local weather to ensure optimized performance.

The Solar Energy Research Institute of Singapore (SERIS) conducts comprehensive research on photovoltaic modules and systems tailored for the tropics. The results presented here from the analysis of PV systems in Singapore (section 2) arise from a project on optimizing PV systems performance specifically for tropical regions. In the subsequent section 3, the results of the SERIS research are presented. Section 4 compares the analysis observed in tropical Singapore with 3 PV systems in Brazil, under similar weather conditions, although with slightly more defined seasons. The findings of this paper are discussed in section 5 and conclusions are given in the final section.

2. HIGH PERFORMANCE SYSTEMS FOR TROPICAL REGIONS RESEARCH

The 3-year research project "High performance PV systems for tropical regions – optimization of system performance" started in May 2009. As part of the project, 12 sites with PV systems across Singapore are monitored (Fig. 1). Some of the sites house 2 or more sub-systems, e.g. one of the sites has 3 systems, one of monocrystalline technology, one multicrystalline and one thin-film. In total, 17 sub-systems are currently under monitoring. Site selection was based on the maximum possible diversity of PV systems in Singapore, in terms of geographic spread around the island, variety of PV technologies (mono-, multi-crystalline and thin-film) and system sizes (ranging from a couple of kWp to ~170 kWp).

Figure 1- Distribution and location of the 12 sites with PV systems around Singapore being monitored by SERIS under its PV systems performance research (shown as blue circles). The triangle represents the location of the National University of Singapore (NUS), where SERIS is located.

For this paper, 10 of such PV systems were selected with the goal of representing the several types of installations found in Singapore. Their basic characteristics are shown in Tab. 1. It can be seen that even though Singapore is located at 1 degree north of the equator, theoretically calling for a flat installation, the preferred tilt angle is approximately 10 degrees, which facilitates a self-cleaning effect of the modules by the rain. The proximity to the equator allows for no particular azimuth being predominant, with most PV systems installed along the building geometry.

Table 1. Basic information from the 10 PV systems under analysis in this paper.

PV	Technology	Inclination [degrees]	Azimuth [0-360 degrees]
A	multicrystalline	5.8	220 SW
B	multicrystalline	5.8	130 SE
C	multicrystalline	10.1~16.0	130 SE
D	multicrystalline	10.0	10 N
E	monocrystalline	10.0	0 N
F	multicrystalline	10.0	190 S
G	multicrystalline	0.0	0 N
H	microcrystalline	6.0	250 SW
I	amorphous silicon	10.0	220 SW
J	amorphous silicon	11.6	50 NE

The monitoring systems of the project were commissioned throughout 2010 so the data shown in this paper amount for an entire year, thus eliminating any seasonal variations between months.

Module temperatures are measured with PT-100 probes, class B, mounted on the back of the module (±0.2 K of uncertainty) and further secured with thermal insulating tapes. The ambient temperature probe is mounted on the vicinity of the PV system and protected with a weather shield against the elements (also ±0.2 K of uncertainty). The irradiance on the plane-of-array is measured by silicon sensors calibrated at Fraunhofer ISE’s CalLab, guaranteeing a very high precision for this kind of measurements (±2% uncertainty). The next section will cover the analysis of the results of the research in Singapore.

3. RESULTS OF MODULE TEMPERATURE IN SINGAPORE

3.1 Methodology of the investigation

A full year of data has been selected for this analysis of the 10 PV systems under investigation. To filter out noise, especially during sunrise and sunset, which may include surroundings and horizon shading, only data recorded with irradiances values above 200 W/m^2 are taken into consideration. The relationships between irradiance (G_{mod}) and module (T_{mod})/ambient (T_{amb}) temperatures are shown in Fig. 2. In this analysis, other environmental effects such as wind speed, air pressure and humidity were not investigated, with the option for a more semi-quantitative approach evaluating such effects as rooftop material, ventilation, module framing and other environmental aspects.

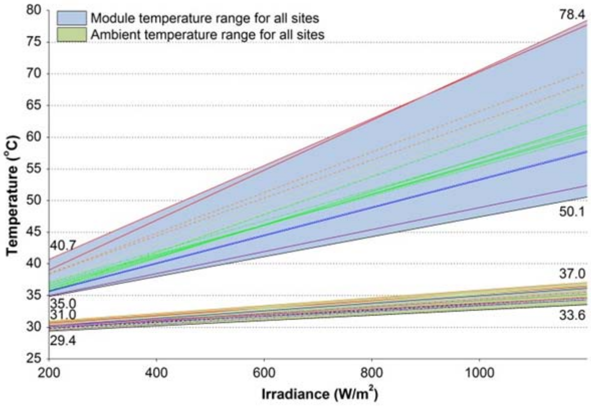


Figure 2- Dependence of module and ambient temperature versus the irradiance level for all systems analysed, with each coloured line representing PV systems under study. The blue range covers variations of module temperature of systems, with only 5.7°C variation at a level of irradiance of 200 W/m^2 but 28.3°C at irradiances of 1,200 W/m^2. Conversely, ambient temperature (green range) varies very little with varying irradiance at the sites.

It can be seen that the variation of ambient temperature with irradiance in the several sites have a similar behaviour pattern within Singapore (country area of ~700 km^2). When irradiance varies from 200 W/m^2 to 1,200 W/m^2, ΔT_{amb} varies from 1.6°C to 3.4°C only. However, a much wider range is observed for the module temperature variation, where ΔT_{mod} varies from 5.7°C to 28.3°C. This indicates that the variation of module temperature among sites is affected only marginally by the variance in ambient temperature and other factors must cause such wide spread of values.

In order to eliminate the effects of ambient temperature, the following formula was used for the further analysis:

$$\Delta T = T_{mod} - T_{amb} = k \cdot G_{mod} \qquad (2)$$

Fig. 3 shows the scatter plot of the data points of ΔT from PV system A vs. irradiance. The linear fit ($R^2 = 0.8$) of those points yield the Ross coefficient (k) which is given by the slope of the straight line. For each system, such a linearization was performed and the coefficients derived used as a semi-quantitative and comparative analysis of the factors that influence module temperature of the PV systems investigated. The delta between R^2 values of approximately 0.8 for the linear fits conducted and a perfect fit of 1.0 could be explained by wind influences, however, were not the target of the investigation in Singapore where annual average wind speeds are very small (< 3.0 m/s).

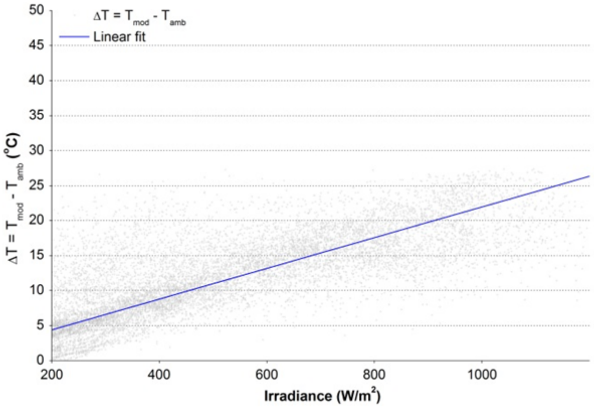


Figure 3- Scatter plot and linear fit according to equation 2 for system A. The slope of the linear fit equates to the Ross coefficient, k.

The subsequently calculated slopes for the 10 PV systems yield the results shown in Fig. 4. According to the inclination of the lines (from lowest to highest values), six patterns were observed (named P1 through P6). The derived Ross coefficients for the patterns are:

P1, 0.017° C·m^2/W
P2, 0.022° C·m^2/W
P3, 0.024° C·m^2/W
P4, 0.027° C·m^2/W
P5, 0.031° C·m^2/W
P6, 0.037° C·m^2/W

The differences in slope are considerable, with more than a factor of 2 between P1 and P6.

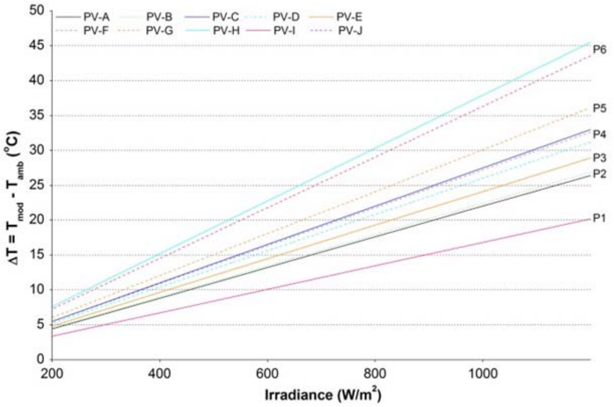


Figure 4- Module temperature rise over ambient temperature as a function of irradiance for the 10 PV systems under investigation (A through J). The systems have been grouped into 6 different patterns (P1 through P6).

3.2 Analysis of contributing factors

From the analysis conducted in Singapore on this topic (Ye *et al.*, 2012), it can be seen that 4 influencing factors contribute to the variation of the Ross coefficient for the PV systems: i) rooftop material, ii) ventilation, iii) module framing and iv) other environmental conditions. The observations of the systems resulted in the creation of Tab. 2 which took into account the rooftop material underneath each system and the distance between modules and rooftop. The rooftop index was introduced with 4 categories as shown in Tab. 3.

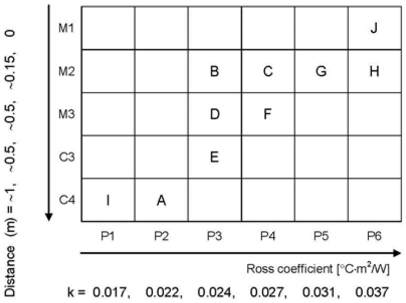
Table 2. Rooftop material and roof distance index.

PV	Rooftop material	Roof distance index
A	Concrete	4
B	Metal	2
C	Metal	2
D	Metal	3
E	Concrete	3
F	Metal	3
G	Metal	2
H	Metal	2
I	Concrete	4
J	Metal	1

Table 3. Roof distance index

Index	Rooftop distance to module	Description
1	0.0 m	Fully attached to rooftop
2	0.1-0.2 m	Small distance from rooftop
3	~ 0.5 m	Slightly ventilated with limited air flow
4	>1 m	Well-ventilated

All systems were categorized according to their k-value and the combination of rooftop material and rooftop distance. The resulting matrix in Fig. 5 was drawn, with "M" representing systems that were installed on metal rooftops and "C" systems installed on concrete rooftops.



	P1	P2	P3	P4	P5	P6
M1						J
M2			B	C	G	H
M3			D	F		
C3			E			
C4	I	A				

Figure 5- Categories for 10 PV systems under monitoring according to individual k-values, rooftop material and rooftop distance index (M = metal, C = concrete).

System J, for example, is installed on a metal rooftop and has a distance index of 1 (fully attached to the rooftop). This system can be seen in Fig. 6 (left) and was categorized as "M1" in the matrix. The right-hand system in Fig. 6 was categorized as "M3" due to being on top of a metal roof with a distance of ~ 0.5 m. Other examples of the classification are seen on Fig. 7 – the left-hand system selected as "C3", concrete rooftop and average distance between modules and roof of ~0.5 m; and the right-hand system categorized as "C4", being also on top of a concrete roof, but with a gap beyond 1 m, allowing for much better ventilation compared to other systems.

Figure 6- PV systems under monitoring on metal roof.

The four influencing factors have the following impacts on PV module temperatures:

i) Rooftop material – compared with concrete roofs, metal roofs show higher values of k. Obviously, metal is a better heat conductor than concrete, especially with an insulation layer between these types of rooftops to prevent heat from going into buildings. This aspect contributed to k values being 30% higher for metal roofs over concrete roofs;

ii) Ventilation – the distance between modules and roof is the biggest contributor to the cooling effect of the modules (e.g. system F having more ventilation space than system G), but roof obstructions and exposure of locations also play a contributing role. The distance indices of systems B and H, for example, are the same and both systems are installed on metal roofs, however system H is installed on top of a house, surrounded by many other houses in a neighbourhood, partially blocking airflow, whereas system B is installed on the top level of an industrial plant with open air spaces in all directions. The ventilation aspect is by far the largest influencing factor identified, with beneficial effects on k of up to 50%;

iii) Module framing – the frame of PV modules, although serving as protection on the laminate edges, can cause lesser air circulation around the modules. Systems B and C are installed at the same site, but system B is a frameless module type. The effect on k was derived to be approximately 10% less for the frameless type;

iv) Other environmental aspects – the surroundings of the system location can contribute to the macro environment of the PV system. Site I for example is located near a large nature reserve in Singapore, which could explain why it is cooler than system A, although technically similar to it. Whenever possible, such favourable environment conditions could contribute to 20% lower values of k.

Figure 7- PV systems under monitoring on concrete rooftops.

4. COMPARISON OF RESULTS IN TWO TROPICAL REGIONS

The Universidade Federal de Santa Catarina (UFSC) has been at the forefront of photovoltaic research in Brazil for more than 15 years. Among the notable results is the installation and monitoring of the country's first grid-connected PV system, in operation since 1997 (Rüther *et al.*, 2010).

For the comparative analysis of the systematic patterns developed in Singapore, three systems in Brazil were identified and their monitoring data analysed similarly to the systems from the SERIS research, that is:

- Ambient and module temperature were recorded as well as irradiance on the plane-of-array of the PV systems;
- A full year of data has been collected and analysed, thus considers any seasonal variations in each region;
- For the linear fit (as in Fig. 3), only data with irradiance values above the threshold of 200 W/m^2 were taken into consideration.

Fig. 8 shows the locations of the PV systems in Brazil. Two of the systems are located in the southern part of the country, in the island of Florianópolis, state of Santa Catarina, at the UFSC campus. The third system is located in the city of Belo Horizonte, state of Minas Gerais. Tab. 4 shows the basic characteristics of the PV systems under investigation.

Figure 8- Map of Brazil with the two locations of the systems under investigation – Belo Horizonte and Florianópolis.

Table 4. Location of the 3 PV systems under investigation in Brazil and their characteristics.

PV	System location	Coordinates	Technology	Inclination	Azimuth
BR1	Florianópolis, SC	27°36’S, 48°31’W	amorphous silicon	27°	0 N
BR2	Florianópolis, SC	27°36’S, 48°31’W	microcrystalline	6°	30 NE
BR3	Belo Horizonte, MG	20°5’S, 43°59’W	monocrystalline	12°	50 NE

System BR1 is the previously mentioned first grid-connected PV system of the country and has operated well over the past 14 years. The system is installed on top of the Mechanical Engineering Department (Fig. 9, left). The modules on system BR1 are partially overhanging the building ledge (25% of it), with the majority of the module area (75% of it) having around 1 m distance to the concrete floor of the roof.

Figure 9- System BR1 (left) has been under operation for 14 years and it was the first grid-connected PV system in Brazil. It is installed at the Mechanical Engineering Department building of UFSC. System BR2 (right) is also located inside the UFSC campus in Florianópolis.

System BR2 (Fig. 9, right) was installed more recently (~3 years). The microcrystalline technology PV modules have been installed on a metal structure which serves as a shelter for a break-out area.

The third system under investigation (BR3, Fig. 10, left) is the first residential grid-connected PV system of the state of Minas Gerais. The system started operations in March 2010 and is installed on the top of a ceramic tile rooftop with distance between modules and tiles of around 5-10 cm. A schematic of this roof is represented in Fig. 10 (right), where an air gap acts as a thermal insulator cushion between the exterior and interior of the house.

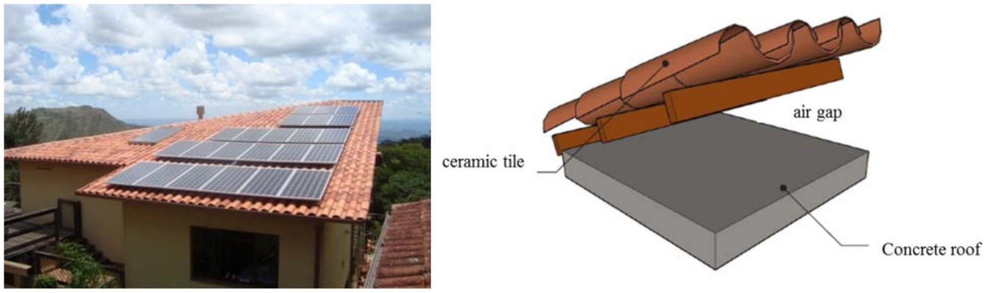


Figure 10- System BR3 (left) is the first residential grid-connected PV system in the state of Minas Gerais. A schematic of this roof can be seen on the right-hand side of the figure.

5. DISCUSSIONS

Fig. 12 combines the results from Singapore (as described in section 3) with the findings from the systems investigated in Brazil. The related slopes for BR1, BR2 and BR3 are:

BR1, 0.020° $C \cdot m^2/W$
BR2, 0.038° $C \cdot m^2/W$
BR3, 0.034° $C \cdot m^2/W$

The fact that system BR2 is close to the PV system in Singapore with the highest k-value (category P6) is a good indication that full contact between modules and metal structure will create higher module temperatures and thus reduce module and system efficiencies - irrespective of the location.

For system BR1, the Ross coefficient lies between categories P1 and P2, in-line with expected results derived from the fact that it is mounted on a concrete rooftop with good ventilation. As previously mentioned and seen from the system in Fig. 9, the overhanging of the modules guarantees good ventilation of air circulating the building.

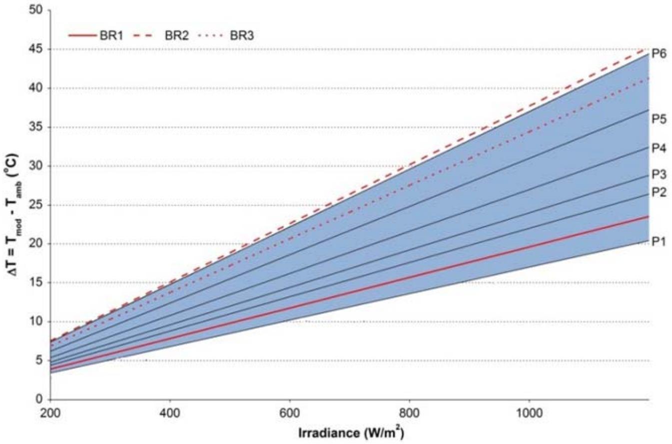


Figure 11- Spectrum of slopes (different Ross coefficients, k) ranging from P1 to P6 from the research of SERIS (blue area). The Brazilian systems fell within expected ranges according to their installation conditions (roof distances and material).

System BR3, although located at a latitude closer to the equator when compared to systems BR1 and BR2, shows similar ambient temperature patterns as Florianópolis (winter temperatures in the 10-15°C and summer temperatures in the 30-35°C range). This can be explained as the house is located on the outskirts of the city, at an altitude of ~1,500 m (versus an approximate average altitude of 900 m for Belo Horizonte). The PV module temperature graph, however, has a much higher value of k (0.034° $C \cdot m^2/W$), which can be explained by the poor ventilation between the modules and the roof ceramic tiles. Also, most of the wind patterns observed at the site come from the valley at the south, which can be seen at the back of Fig. 11 (left-hand side). That air flow clearly is blocked by the orientation of the house and the rooftop, thus preventing the system from being better cooled by natural winds.

Therefore, the poor ventilation compared to BR1 as reference results in an approximately 50% higher k-value, while the blocked natural wind prevent the system from leveraging the 20% from positive environmental conditions, making its temperature dependence ~70% worse than BR1. The resulting k of 0.034° $C \cdot m^2/W$ compares very well to a similar type of system in Singapore (k = 0.037° $C \cdot m^2/W$) where modules are also placed on a residential house with a small distance to a relatively "hot" roof (thin metal sheets with similar characteristics than ceramic roof tiles) and natural winds are very little (Fig. 12).

Figure 12- Residential PV system in Singapore. Metal roof and poor ventilation in the area make this site one with the highest k-values of systems under investigation.

6. CONCLUSIONS

The Ross coefficients were calculated for 10 PV systems in Singapore based on their variations of ΔT (= module temperature – ambient temperature) as a function of in-plane irradiance. The analysis showed a wide range of PV module temperature rise over the - relatively moderate - increase of the ambient temperature, indicating that other factors than ambient temperature must affect the operating temperature of PV modules.

Those factors have been identified (such as rooftop material, ventilation, module framing and other environmental aspects) and used for a semi-quantitative analysis. In parallel, systems in Brazil have been investigated with the same methodology and shown to have a similar pattern of module temperature behaviour as in Singapore.

In order to optimize the performance of PV systems in constantly hot climates, it is paramount to keep PV module temperatures as low as possible. Through proper site selection and leveraging on knowledge presented in this paper, module temperature rise over ambient temperature can be substantially reduced. As the monitoring results show a factor greater than 2 - between the lowest and the highest temperature rise - and with a 0.45%-drop for every 1◦ C higher temperature of silicon wafer-based modules (and about half of that for thin-film technologies), this can be directly translated into an economic benefit from higher energy output achieved by installing cooler systems.

The applicability of the methodology is valid for different locations in the tropics. The increasing importance of upcoming large PV markets in Asia and Latin America make such system design and installation techniques (for keeping module temperatures low), even more relevant - knowing that temperature losses account for ~50% of system losses in tropical climates.

Acknowledgments

SERIS would like to acknowledge the sponsorship of the project "High Performance Photovoltaic Systems for Tropical Regions" by the National Research Foundation (NRF) of Singapore under the Clean Energy Research Program (CERP), research grant number NRF2008EWT-CERP02-031.

UFSC would like to thank the Alexander von Humboldt Foundation (Germany) and the Brazilian National Research Council (CNPq – Brazil) for sponsoring the project for system BR1 shown in this paper. UFSC would also like to thank TRACTEBEL for sponsoring the project for system BR2.

Both groups would like to thank the owners of system BR3 for allowing the monitoring of their PV system.

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